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CP Violation in the Decay of Neutral Higgs Boson into $t - \bar{t}$ and $W^+ - W^-$

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We investigate a potentially large CP violating asymmetry in the neutral Higgs boson decay into a heavy quark pair or a $W^+ - W^-$ pair. The source of the CP nonconservation is in the Yukawa couplings of the Higgs boson which can contain both scalar and pseudoscalar pieces. One of the interesting consequence is the different rates of the Higgs boson decays into CP conjugate polarized states. The required final state interactions can be either the strong or the electroweak interactions. The CP violating asymmetry can manifests itself in the asymmetry in the energies of the secondary decay products of these heavy quarks and W bosons. Such asymmetry can be measureable in the future colliders such as SSC or LHC.

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The physics related to the Higgs boson is the most mysterious part of the Standard Model. It is widely expected that whatever information we can obtain about the Higgs sector from the next generation colliders will give us hints about the potential new physics beyond the Standard Model. Most of analyses about the search for Higgs bosons, in the Standard Model or beyond, often ignore potential CP violation. However, in these models, the lightest neutral Higgs boson can have interesting CP violating phenomena. In some sense, as we shall elaborate later, the CP violating aspect may be the most interesting part of the Higgs boson physics beyond the Standard Model once a neutral Higgs is identified.

In this letter, we investigate an interesting signature of CP violation in the neutral Higgs decay into a heavy quark pair $Q\bar{Q}$ or a W^+W^- pair. For the heavy quark $Q\bar{Q}$ mode, to the lowest order in the final state quark mass, the polarizations of the quarks are either $Q_L\bar{Q}_L$ or $Q_R\bar{Q}_R$. (Note that we have adopted the notation that \bar{Q}_L is the antiparticle of Q_R and should be left handed.) These two modes happen to be CP conjugate of each other. Therefore one can immediately consider the CP asymmetry in the event rate difference, $N(Q_L\bar{Q}_L) - N(Q_R\bar{Q}_R)$. For the W pair mode, the two polarization modes $W_L^+W_L^-$ and $W_R^+W_R^-$ are also CP conjugate of each other. (Here we denote the states of helicities $-1, 1$ and 0 by L, R and \parallel respectively.) Therefore, their difference in the decay rates, $N(W_L^+W_L^-) - N(W_R^+W_R^-)$, signals CP violation. For the Z pair mode, one can look at the similar asymmetry $N(Z_LZ_L) - N(Z_RZ_R)$ also.

A method in detecting the asymmetry $N(Q_L\bar{Q}_L) - N(Q_R\bar{Q}_R)$ was proposed recently in Ref.[1]. One assumes that the quark Q decays semileptonically through the usual $V - A$ weak interaction. For a lighter quark (such as the b quark), the information about polarization is probably washed away in the soft process of hadronization before its subsequent decay. However, for a heavy quark such as the top quark, since

the hadronization time is much longer than the decay time[2], one can analyze polarization dependence of its decay at the quark level. The top quark first decays into a b quark and a W^+ boson, which subsequently becomes $\bar{l}\nu$. For heavy top quark, the W^+ boson produced in top decay is predominantly longitudinal. Due to the $V - A$ interaction, the b quark is preferentially produced in the left-handed helicity. So the longitudinal W^+ boson is preferentially produced along the direction of the top quark polarization. Therefore the anti-lepton \bar{l} produced in the W^+ decay is also preferentially in that direction. At the rest frame of t , the angular distribution[3] of the produced \bar{l} has the form $1 + \cos \psi$, with ψ as the angle between \bar{l} and the helicity axis of t . When the Higgs boson decays, the top quark is produced usually with nonzero momentum. As a result of the Lorentz boost, the anti-lepton \bar{l} produced in the decay of the right handed top quark t_R has a higher energy than that produced in the decay of the left handed top quark t_L . Similarly, the l lepton produced in the decay of \bar{t}_L has a higher energy than that produced in the decay of \bar{t}_R . Consequently, in the decay of the pair $t_L\bar{t}_L$ the lepton from \bar{t}_L has a higher energy than the anti-lepton from t_L ; while in the decay of $t_R\bar{t}_R$ the anti-lepton has a higher energy. Therefore one can observe $N(t_L\bar{t}_L) - N(t_R\bar{t}_R)$ by measuring the energy asymmetry in the resulting leptons[4].

For asymmetry in the W^+W^- mode, one can look at the leptonic decays of the W gauge bosons. We are interested in the transverse W bosons in this case. In the rest frame of W^+ , which decays into $\bar{l}\nu$, the angular distribution of \bar{l} has the form $(1 + \cos \psi)^2$, with ψ as the angle between \bar{l} and the helicity axis along which the spin projection of W is one. Similar to previous analysis, the anti-lepton in the decay of W_R^+ has a higher energy than the lepton from the W_R^- , while the lepton in the decay of W_L^- has a higher energy than the anti-lepton from the W_L^+ . Therefore, the relative energy between the lepton and the antilepton in the decay of a W^+W^- pair can be

translated into the information about the polarization of W bosons. The asymmetry is much harder to detect in the leptonic final states for the case of Z pairs. Because of the dominance of the axial-vector coupling to leptons, there is only a weak angular dependence for the outgoing leptons. However it is present in principle.

In order to generate the asymmetries $N(t_L \bar{t}_L) - N(t_R \bar{t}_R)$ or $N(W_L^+ W_L^-) - N(W_R^+ W_R^-)$, it is necessary to include effects of the final state interactions in order to escape from the hermiticity constraint at the tree level due to the CPT theorem. These final state interactions, as shown in Fig. 1, can come from the strong, the electroweak, or the Higgs corrections to the $HQ\bar{Q}$ or HW^+W^- vertices.

In the $H \rightarrow t\bar{t}$ channel, CP non-conservation occurs in the complex Yukawa coupling,

$$\mathcal{L}_{Ht\bar{t}} = -(m_t/v)\bar{t}(AP_L + A^*P_R)tH, \quad v = (\sqrt{2}G_F)^{-\frac{1}{2}} \simeq 246 \text{ GeV}. \quad (1)$$

The complex coefficient A is a combination of model-dependent mixing angles. Simultaneous presence of both the real part $A_R = \text{Re}A$ and the imaginary part $A_I = \text{Im}A$ guarantees CP asymmetry. For example, at the low energy regime, it can give rise to the electric dipole moment of elementary particles [5, 6]. Here we will show that CP nonconservation manifests itself in the event rate difference in collider experiments. We denote δ^{QCD} , δ^γ , δ^Z , δ^H , δ^{WW} , δ^{ZZ} , as contributions in CP asymmetry due to the exchange of the gluon, the photon, the Z boson, the Higgs bosons, or those with intermediate states of a W pair or a Z pair respectively,

$$\frac{N(t_L \bar{t}_L) - N(t_R \bar{t}_R)}{N(\text{all } t\bar{t})} = \frac{\delta^{\text{QCD}} + \delta^\gamma + \delta^Z + \delta^H + \delta^{WW} + \delta^{ZZ}}{\beta_t A_R^2 + A_I^2}, \quad (2)$$

with $\beta_t^2 = 1 - 4m_t^2/M_H^2$. The one-gluon exchange gives large CP asymmetry,

$$\delta^{\text{QCD}} = (C\alpha_S/2)\text{Im}(A^2)(1 - \beta_t^2), \quad (3)$$

with the color factor $C = 4/3$. It is interesting to note that the imaginary part of the one-loop graph contributes a factor of A_R while the tree graph contributes A_I (that is, the pseudoscalar coupling). When $A_I \sim A_R$, the asymmetry is of order of the strong coupling α_S , about 10^{-1} . Fig. 2 shows how such asymmetry depends on M_H . Note that there is no strong constraints[5,6] on $\text{Im}(A^2)$, which can easily be of order one.

The electromagnetic correction δ^γ is obtained by replacing α_S by the QED coupling α , and C by $4/9$, the charge squared of the t -quark. The result is negligible. The contribution by the Z -exchange is

$$\delta^Z = \frac{\sqrt{2}G_F m_t^2}{8\pi} \text{Im}(A^2) \left\{ \left[F\left(\frac{M_H^2 \beta_t^2}{M_Z^2}\right) - 2 \right] \beta_t^2 + \frac{M_Z^2}{M_H^2} F\left(\frac{M_H^2 \beta_t^2}{M_Z^2}\right) [1 + (1 - 8x_W/3)^2] \right\}. \quad (4)$$

Here the function $F(x) = 1 - x^{-1} \log(1+x)$, and $x_W = \sin^2 \theta_W \approx 0.22$. The term with the factor $(1 - 8x_W/3)^2$ is due to the part of the one-loop graph in which both vertices of Z boson are vectorial while the rest are due to the part in which both vertices of Z are axial-vectorial. The parts with one axial vector vertex and one vector vertex do not contribute. For the part involves only the axial vector vertices of Z boson, the tree graph can contribute either scalar or pseudoscalar coupling. Contribution from the Higgs bosons is more complicated. In general, there are more than one neutral Higgs bosons H_i , with Yukawa couplings to the t -quark of the form, $\mathcal{L}_{H_i t t} = -(m_t/v) \sum_i \bar{t}(a_i P_L + a_i^* P_R)t H_i$. The coefficient A is only one of these a_i . The overall effect from all Higgs bosons is

$$\delta^H = \frac{\sqrt{2}G_F m_t^2}{8\pi} \sum_i F\left(\frac{M_H^2 \beta_t^2}{M_{H_i}^2}\right) \left[\beta_t^2 \text{Im}(A^2 a_i^{*2}) + (1 - \beta_t^2) \text{Im}(A) \text{Re}(A |a_i|^2 + A a_i^{*2}) \right]. \quad (5)$$

In a simplified case of the decay of the lightest Higgs boson H , if the effects of heavier Higgs bosons can be neglected, the formula is much reduced as $a_H = A$ and the first

term in the bracket of the above equation vanishes. Numerical study shows that δ^H is very small in this scenario.

There are important contributions from processes involving W^+W^- or ZZ intermediate states as shown in Fig. 1. The amplitudes depend on the the vertices,

$$\mathcal{L}_{HWW,HZZ} = Bg_2 H[M_W W^{+\nu} W_\nu^- + \frac{1}{2}(M_Z/\cos\theta_W)Z^\nu Z_\nu]. \quad (6)$$

In any model, the scalar boson that couples to the W pair or Z pair is the scalar partner of the unphysical Higgs boson. This scalar boson is in general not a mass eigenstate. Therefore we parametrize its coupling by a phenomenological coefficient B in addition to the usual $SU_L(2)$ gauge coupling g_2 . The coefficient B represents the mixing factor needed to reach the mass eigenstate. It reduces to unity in the Standard Model with one single Higgs doublet. For the diagrams with W^+W^- intermediate states, we obtain the CP asymmetry,

$$\delta^{WW} = -\frac{\sqrt{2}G_F M_W^2 B A_I \beta_W \beta_t}{4\pi} \left\{ \left[\frac{3\beta_t^2 - 2\beta_W^2 - 1}{2\beta_t^2} + \frac{1 - \beta_t^2}{\beta_t^2(1 - \beta_W^2)} \right] L(\beta_W, \beta_t) - 2L(\beta_W, \beta_t) + 2 + \frac{1 + \beta_W^2}{1 - \beta_W^2} \right\}, \quad (7)$$

where $\beta_W^2 = 1 - 4M_W^2/M_H^2$, and the function

$$L(x, y) \equiv 1 + \frac{x^2 - y^2}{2xy} \log \left| \frac{x - y}{x + y} \right|. \quad (8)$$

Also, for the diagrams with ZZ intermediate states, we obtain the CP asymmetry,

$$\delta^{ZZ} = -\frac{\sqrt{2}G_F M_Z^2 B A_I \beta_Z}{16\pi\beta_t} \left[\left(1 - \frac{8}{3}x_W\right)^2 \left(1 + \frac{1 + \beta_Z^2 + 2\beta_t^2}{4\beta_Z\beta_t} K\right) (1 - \beta_Z^2) + (1 - \beta_Z^2) \left(1 + \frac{1 + \beta_Z^2 - 2\beta_t^2}{4\beta_Z\beta_t} K\right) + \frac{1 - \beta_t^2}{1 - \beta_Z^2} \frac{(1 + \beta_Z^2)^2}{2\beta_Z\beta_t} K + 2 \frac{1 + \beta_Z^2}{1 - \beta_Z^2} \right], \quad (9)$$

with

$$K = \log \left| \frac{1 + \beta_Z^2 - 2\beta_t\beta_Z}{1 + \beta_Z^2 + 2\beta_t\beta_Z} \right|. \quad (10)$$

The first term in the square bracket is the contribution where both of the Z couplings with the top quark are vectorial. The remaining two terms correspond to the contribution where both couplings are axial-vectorial. Also note that the one-loop induced vertex is always scalar and the A_I factor arises from the tree level amplitude. Numerical study shows that δ^{WW} and δ^{ZZ} are very important for the natural scenario $A_R \sim B$. Their contributions can dominate when M_H is large as illustrated in Fig. 2. In this letter, we shall ignore the contributions due to tri-Higgs couplings because they are more model dependent in general. Also, this type of contributions disappears, due to the vanishing imaginary part, when the decaying Higgs boson is the lightest Higgs boson. In any case, this type of contribution will not affect our results very much as long as no accidental cancellation occurs.

Since CP violation in Eq.(1) would disappear if the top quark were massless, one may wonder why the above formulas for δ^{ZZ} and δ^{WW} are not proportional to m_t . The answer is that, in the denominator, the leading (tree) level contribution also has a factor of m_t in our parametrization in Eq.(1). The m_t required physically in the numerator is artificially cancelled by this factor in the denominator.

For the W pair production, the tree level amplitude, parametrized by B , interferes with the fermion-loop amplitude (Fig. 3) of the b quark exchange to produce the CP violating asymmetry. The resulting asymmetry is

$$\frac{N(W_L^+ W_L^-) - N(W_R^+ W_R^-)}{N(W_L^+ W_L^-) + N(W_R^+ W_R^-)} = \frac{\sqrt{2} G_F m_t^2}{4\pi B} A_I \frac{\beta_t}{\beta_W} L(\beta_t, \beta_W). \quad (11)$$

Fig. 4 shows such asymmetry, which is sizable for large m_t . Note that, for a heavy Higgs boson, its leading mode is neither $W_L^+ W_L^-$ nor $W_R^+ W_R^-$, but the longitudinally polarized state of $W_{||}^+ W_{||}^-$. However, the $W_{||}^+ W_{||}^-$ state is CP self conjugate and can not provide the CP asymmetry we are looking for. As we discussed earlier, this

asymmetry can be detected by measuring the energy asymmetry of the two charged leptons in the decay of the two W 's. One can also sum over different lepton flavor channels to increase the rate.

Similar CP asymmetry can be formed between the $Z_L Z_L$ and the $Z_R Z_R$ pairs,

$$\frac{N(Z_L Z_L) - N(Z_R Z_R)}{N(Z_L Z_L) + N(Z_R Z_R)} = \frac{\sqrt{2}G_F m_t^2}{4\pi B} A_I \frac{\beta_t}{\beta_W} \left[1 + \frac{K}{4\beta_t \beta_Z} - \left(1 - \frac{8}{3}x_W\right)^2 \frac{K\beta_Z}{4\beta_t} \right]. \quad (12)$$

However it is not clear how feasible one can decode such asymmetry from the final decay products of the Z 's.

In conclusion, we have shown a potential large CP violating asymmetry, naturally of size about 10%, in the decay of the neutral Higgs boson. Production of the Higgs boson in the future hadron colliders, like SSC and LHC, will definitely provide important information[7] on the CP nonconservation.

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- [7] The numerical results and the background analysis of the CP violation in the decay of the neutral Higgs boson will be included in a longer paper, D. Chang and W.-Y. Keung (to be published).

FIGURES

FIG. 1. Feynman diagrams for the process $H \rightarrow t\bar{t}$. The tree amplitude (a) interferes with those one-loop amplitudes with the final state interactions coming from (b) the exchange of a gluon g , a photon γ , a Z gauge boson or a Higgs boson H_i ; (c) the intermediate W^+W^- boson pair; (d) the intermediate ZZ boson pair.

FIG. 2. $[N(t_L\bar{t}_L) - N(t_R\bar{t}_R)]/[N(t_L\bar{t}_L) + N(t_R\bar{t}_R)]$ versus M_H for $m_t = 200$ GeV. The illustration is for the case $A_I = A_R = B = 0.5$.

FIG. 3. (a) The one-loop diagram for $H \rightarrow W^+W^-$ produces the CP violating asymmetry when it interferes with the tree amplitude. (b) The same effect occurs for $H \rightarrow ZZ$.

FIG. 4. $[N(W_L^+W_L^-) - N(W_R^+W_R^-)]/[N(W_L^+W_L^-) + N(W_R^+W_R^-)]$ versus M_H for different values of $m_t=100$ GeV (solid), 150 GeV (dashed), 200 GeV (dotted), and 250 GeV (dash-dotted).

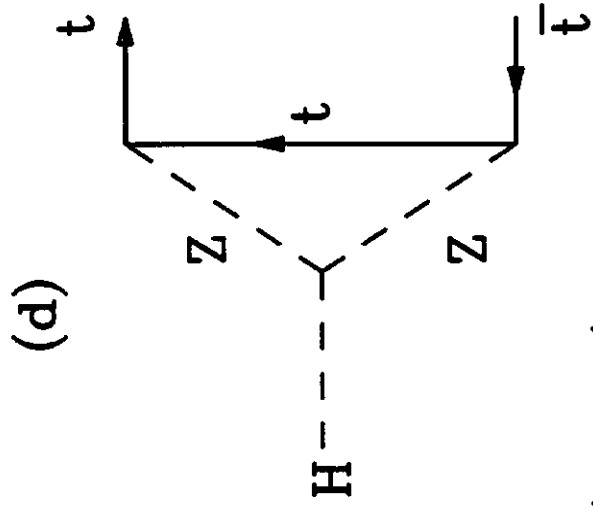
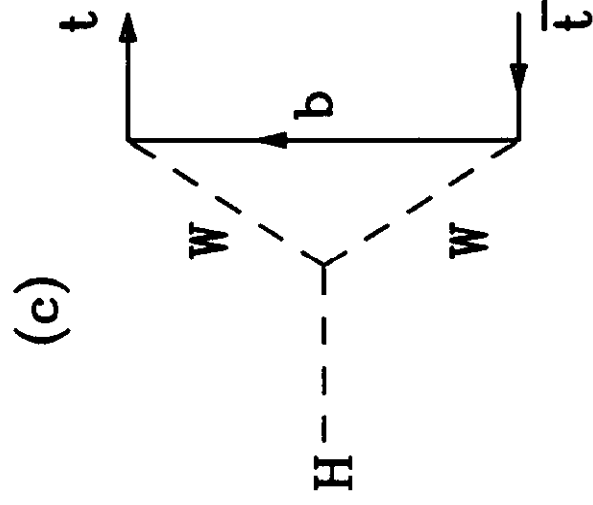
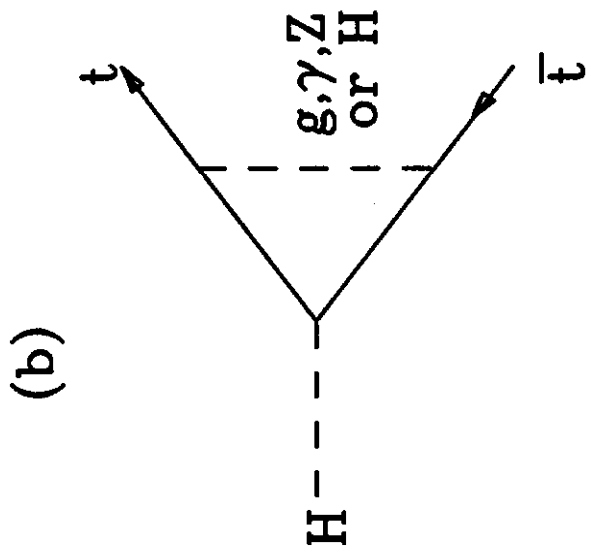
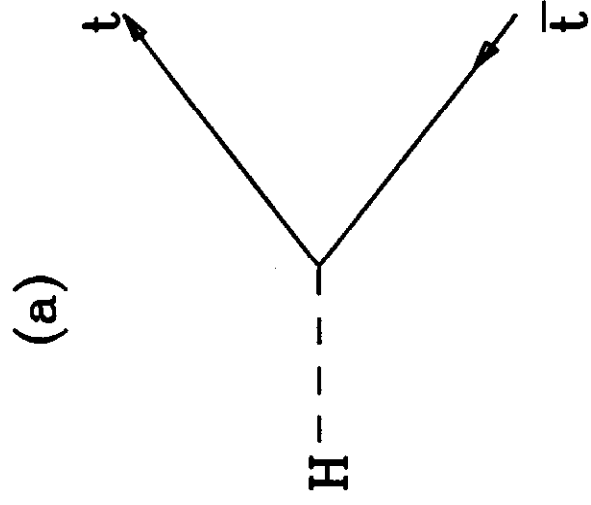
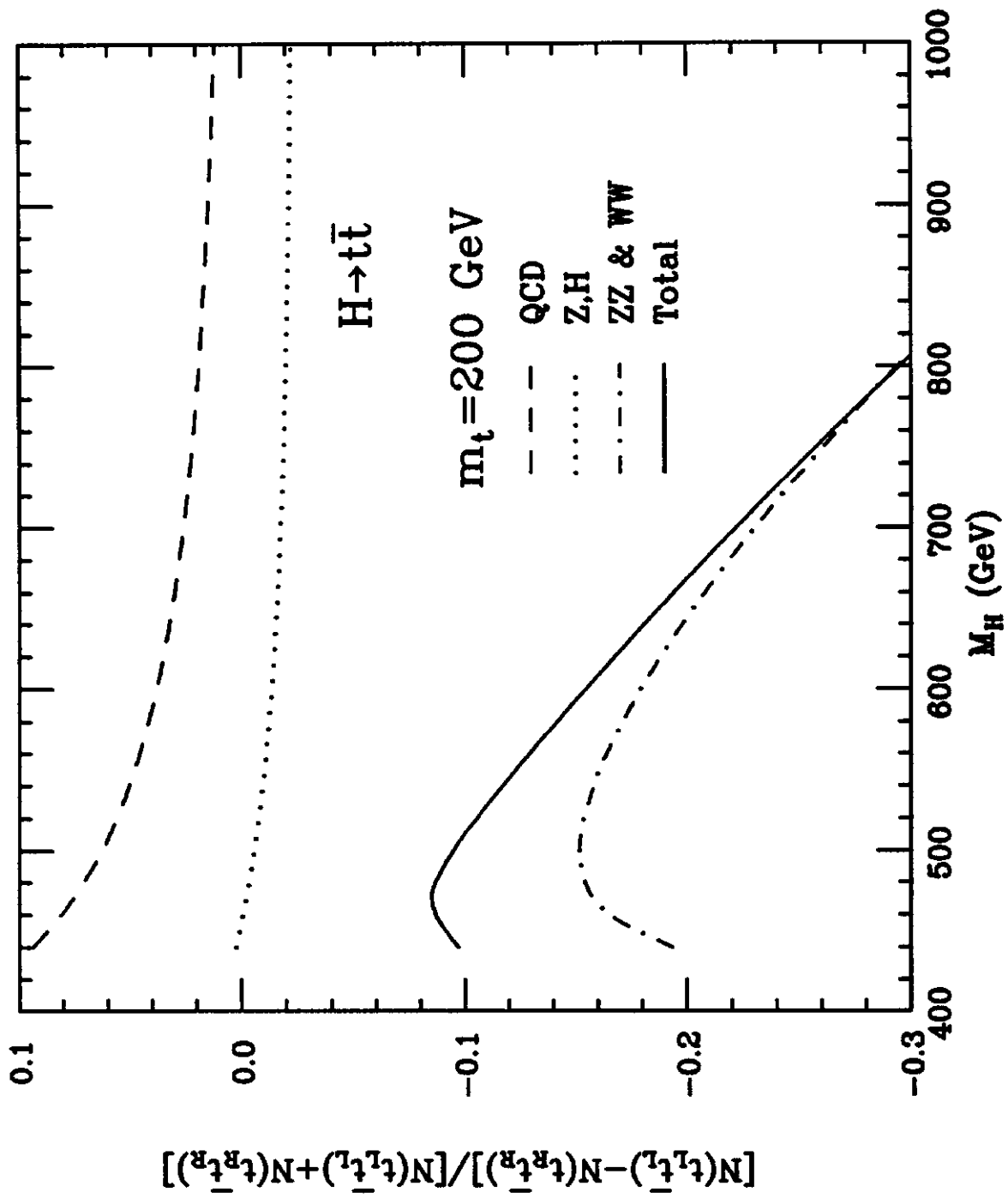


Figure 1

Figure 2



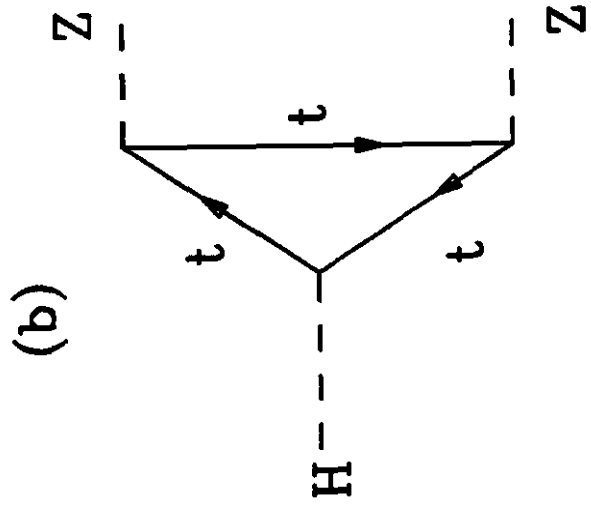
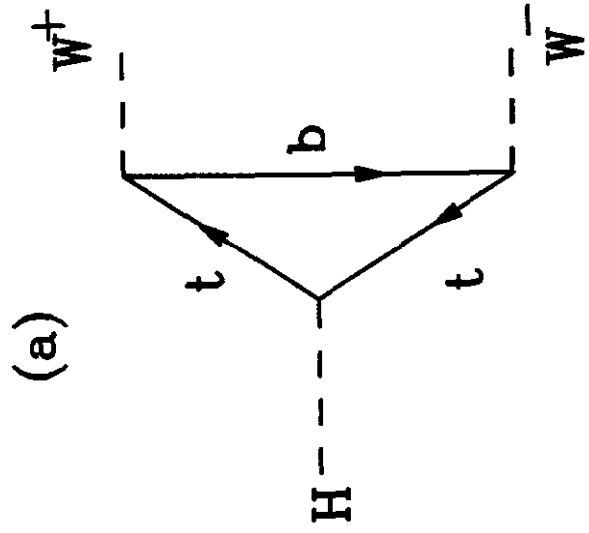


Figure 3

Figure 4

